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Winter Rye Cover Crop Biomass Production, Degradation, and Nitrogen Recycling

Jose L. Pantoja, Krishna P. Woli,* John E. Sawyer, and Daniel W. Barker

ABSTRACT

Winter rye (*Secale cereale* L.) cover crop (RCC) use in corn (*Zea mays* L.) and soybean [*Glycine max.* (L.) Merr.] production can alter N dynamics compared to no RCC. The objectives of this study were to evaluate RCC biomass production (BP) and subsequent RCC degradation (BD) and N recycling in a no-till corn–soybean (CS) rotation. Aboveground RCC was sampled at spring termination for biomass dry matter (DM), C, and N. To evaluate BD and remaining C and N, RCC biomass was put into nylon mesh bags, placed on the soil surface, and collected multiple times over 105 d. Treatments included rye cover crop following soybean (RCC-FS) and corn (RCC-FC), and prior-year N applied to corn. Overall, the RCC BP and N was low due to low soil profile $\text{NO}_3\text{-N}$. Across sites and years, the greatest BP was with RCC-FC that received 225 kg N ha^{-1} ($1280 \text{ kg DM ha}^{-1}$), with similar N uptake as with RCC-FS (27 kg N ha^{-1}). The RCC biomass and N remaining decreased over time following an exponential decay. An average 62% biomass with RCC-FS and RCC-FC degraded after 105 d; however, N recycled was greater with RCC-FS than RCC-FC [22 (80%) vs. 14 (64%) kg N ha^{-1} , respectively], and was influenced by the RCC C/N ratio. The RCC did not recycle an agronomically meaningful amount of N, which limited N that could potentially be supplied to corn. Rye cover crops can conserve soil N, and with improved management and growth, recycling of crop-available N should increase.

UNDERSTANDING crop biomass degradation and nutrient cycling dynamics in cropping systems is critical for efficient resource management (Schomberg et al., 1994). Nitrate can accumulate in soils with N fertilization of cereal crops (Jacinto et al., 2000), and use of a winter RCC has been shown to reduce NO_3 concentration and load in subsurface tile-drainage from corn-based cropping systems (Strock et al., 2004). Because NO_3 moves readily with water through soil to drainage systems, and it often occurs in early spring when row crops are not present, management of N inputs for optimal crop production while minimizing NO_3 loss continues to be a challenge (Dinnes et al., 2002).

Due to concerns about $\text{NO}_3\text{-N}$ delivery to the Gulf of Mexico, local drinking water standards (USEPA, 2007; Hoorman et al., 2009), and soil erosion, government cost share programs providing incentives to farmers for implementing RCC and practicing no-till or strip till are increasing (Vande Hoef, 2015). Farmers are also increasingly interested in practices that can help reduce NO_3 losses as they have begun to understand their role in improving water quality. Therefore, improved nutrient use efficiency, sustainable crop production, and drinking water quality are ongoing needs in the Midwest region of the United States (Lawlor et al., 2008). In the Midwest, corn N fertilization at recommended rates can result in $\text{NO}_3\text{-N}$ losses in tile drainage of 29 to 56 kg N ha^{-1} (Sawyer and Randall, 2008), with a high fraction occurring in springtime drainage. Nutrient management is more challenging for N than other plant nutrients because of its complex cycle and the speed at which N can transform to different chemical forms.

Potential reduction of $\text{NO}_3\text{-N}$ loss between growth cycles of annual crops with an RCC was reported to average about 31% in Midwest corn and soybean production (Iowa State University, 2014). In various research studies, cover crops have been reported to reduce $\text{NO}_3\text{-N}$ loss from 7 to 65 kg ha^{-1} (Dabney et al., 2010; Kaspar et al., 2012), and thus are a viable practice for improving water quality (Kaspar et al., 2001; Qi and Helmers, 2010; Drury et al., 2014; Acuña and Villamil, 2014). Cover crops function by taking up inorganic soil N and holding it in organic forms during springtime N loss periods (Staver and Brinsfield, 1998).

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Abbreviations: BD, rye cover crop biomass degradation; BP, rye cover crop biomass production; CS, corn–soybean; DM, dry matter; RCC, rye cover crop; RCC-C, rye cover crop aboveground biomass carbon; RCC-FC, rye cover crop following corn; RCC-FS, rye cover crop following soybean; RCC-N, rye cover crop aboveground biomass nitrogen.

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Therefore, cover crops have potential to improve N cycling in agricultural fields (Tonitto et al., 2006; Kaspar and Singer, 2011). Additional potential benefits from cover crops include improved infiltration, decreased erosion, enhanced microbial biomass, increased weed suppression, and improved C sequestration and soil organic matter (Kaspar et al., 2001; Franzluebbers, 2005; Sainju et al., 2005; Dhima et al., 2006; Hoorman et al., 2009; Olson et al., 2010; Bernstein et al., 2011; Mirsky et al., 2013; Tabaglio et al., 2013; Moore et al., 2014; McDaniel et al., 2014). An issue with cover crops in the upper Midwest, however, is the cold and generally short period for growth between harvest and spring planting of annual crops (Dinnes et al., 2002). Due to winter hardiness and its potential to utilize residual soil $\text{NO}_3\text{-N}$, RCC is often used as a cover crop in the Midwest region (Feyereisen et al., 2006).

Despite the potential RCC benefits, information about effects on N recycling is unclear. Effectiveness of an RCC in improving N cycling still needs to be addressed when using different N rates, tillage systems, and with variable weather patterns (Qi et al., 2011). The successful use of an RCC in crop rotations depends on appropriate management practices (Ruffo and Bollero, 2003b), including timely termination in the spring to avoid annual crop yield loss or microbial use of plant available N for RCC-BD (Johnson et al., 1998; Parkin et al., 2006).

Negative RCC effects on corn growth and yield (Johnson et al., 1998; Thelen and Leep, 2002; Kramberger et al., 2009; Pantoja et al., 2015) make farmers reluctant to use an RCC or to allow adequate time to grow in the spring (Tollenaar et al., 1993; Vaughan and Evanylo, 1998; Dinnes et al., 2002; Dhima et al., 2006). Lamarca (1996) found that when accumulated cereal cover crop biomass was less than $3000 \text{ kg DM ha}^{-1}$, the strongest negative effect on corn growth was for the 4-wk period after cover crop termination; however, greater cover crop biomass resulted in an extended negative effect. Therefore, farmers attempt to reduce negative RCC effects with early termination in the spring, which allows timely corn planting, but reduces RCC potential benefits. Early termination also allows more time for BD and N recycling (Kaspar and Singer, 2011). However, early termination would diminish the RCC potential to scavenge residual NO_3 . Extending the waiting period could result in late corn planting, something farmers prefer to avoid due to potential yield loss (Cirilo and Andrade, 1994; Duiker and Curran, 2005; Van Roekel and Coulter, 2011).

Differences in weather conditions may affect not only corn and soybean yield, and resultant N uptake, but also RCC BP, fall and spring RCC growth, RCC N accumulation, and nutrient cycling. Residual soil profile $\text{NO}_3\text{-N}$ remaining after crop harvest for RCC uptake is influenced by annual precipitation and

crop yield, and also by late fall and early spring excess precipitation (Strock et al., 2004).

Predicting plant biomass degradation requires knowledge of environmental factors and chemical and physical composition of the biomass (Collins et al., 1990). To have success in N recycling and supply of plant available N to annual crops from RCC BD, the N supply and availability needs to be synchronized with annual crop N uptake (Kaspar and Singer, 2011). Rye cover crop BD and N recycling are mainly a function of air temperature (Farsad et al., 2011; Brennan and Boyd, 2012), biomass quality (Gregory et al., 1985; Ma et al., 1999), cropping history (Parkin et al., 2002), rainfall intensity (Williams et al., 2002), and soil moisture (Schomberg et al., 1994). Potential RCC N recycling is also a function of C and N availability for microbes, rather than only the total amount in RCC biomass (Ruffo and Bollero, 2003b). Steiner et al. (1994, 1999) found that both air temperature and soil moisture should be combined when developing models to describe crop biomass degradation. However, Collins et al. (1990) considered time in first-order kinetics functions (exponential decay) as an accurate and the simplest approach to evaluate degradation of crop biomass.

When adopting RCC as a management practice in corn production systems, farmers would like to know how much N is taken up by an RCC and if and when that N is recycled and available to corn. The objectives of this study were to evaluate RCC N uptake, BD, and N recycling after spring RCC termination in a no-till CS rotation.

MATERIALS AND METHODS

Study Sites

The study reported here was conducted in 2010 and 2011 at four sites in Iowa that were part of an ongoing project evaluating corn and soybean grain yield and N fertilization response to RCC (Pantoja et al., 2015). For the overall project, in the spring 2008 two adjacent study areas were selected at each site (Table 1); Agricultural Engineering and Agronomy Research Farm near Ames [$42^\circ 00' 34'' \text{ N}$; $93^\circ 46' 50'' \text{ W}$; elevation (EL), 333 m], Southeast Research and Demonstration Farm near Crawfordsville ($41^\circ 12' 09'' \text{ N}$; $91^\circ 29' 31'' \text{ W}$; EL, 233 m); Armstrong Memorial Research and Demonstration Farm near Lewis ($41^\circ 18' 48'' \text{ N}$; $95^\circ 10' 49'' \text{ W}$; EL, 400 m), and Northeast Research and Demonstration Farm near Nashua ($42^\circ 55' 54'' \text{ N}$; $92^\circ 34' 37'' \text{ W}$; EL 321 m). A no-till CS rotation was initiated, with both crops present each year and rotated between areas. The year before project establishment all sites were tilled, with Ames and Nashua planted to soybean and Crawfordsville and Lewis planted to corn. There was one no-till crop year before the 2010 study year, therefore, there could be some residual effect on N

Table 1. Soil information for each study site.

Site	Predominant soil series	Textural class	Soil classification
Ames	Clarion	Loam	fine-loamy, mixed, superactive, mesic Typic Hapludoll
	Nicollet	Clay loam	fine-loamy, mixed, superactive, mesic Aquic Hapludoll
Crawfordsville	Mahaska	Silty clay loam	fine, smectitic, mesic Aquertic Argiudoll
	Nira	Silty clay loam	fine-silty, mixed, superactive, mesic Aquic Argiudoll
Lewis	Marshall	Silty clay loam	fine-silty, mixed, superactive, mesic Typic Hapludoll
Nashua	Floyd	Loam	fine-loamy, mixed, superactive, mesic Aquic Pachic Hapludoll
	Clyde	Silty clay loam	fine-loamy, mixed, superactive, mesic Typic Endoaquoll

cycling with the conversion to no-till. Initial soil tests, presented in Pantoja et al. (2015), indicated that soil pH was slightly acidic (6.3–6.6), soil organic matter 41 to 50 g kg⁻¹, and Mehlich-3 soil test P and K were in the Optimum to Very High interpretation categories (Sawyer et al., 2008). Weather data (Fig. 1) was collected at weather stations at each research site and reported by the Iowa Environmental Mesonet Network (Arritt and Herzmann, 2013).

Treatments

The experimental design within each field at each site was a split-plot randomized complete block (RCB). This was the design for RCC-FC in this study, but for RCC-FS was not a split-plot as the N rate plots were not used. There were four replications. The RCC treatment (with and without RCC) was the main plot and six fertilizer N rates (0–225 kg N ha⁻¹ in 45 kg N ha⁻¹ increments) applied to corn the split-plot. The N was applied within 2 wk after planting as urea-ammonium nitrate solution (UAN, 32% N) with coulter-injection to every other row-space (1.52 m spacing). Treatments remained in the same plot locations. Plot size was eight crop rows (0.76 m row spacing) in width and 15 m in length at Ames, Crawfordsville, and Lewis; and six rows in width and 18 m in length at Nashua. For the study presented here, only the RCC plots were used. For RCC-FC, of the six N rates RCC biomass was used from the zero, approximate middle, and highest rates (0, 135, and 225 kg ha⁻¹, hereafter 0N, 135N, and 225N, respectively). For RCC-FS, RCC biomass was used from the main plot across N rates.

The RCC cultivar used each year was cultivar Wheeler and was no-till drill-seeded in the fall after corn and soybean harvest at a rate of 70 kg ha⁻¹. The RCC row spacing was 0.19 m at Ames, 0.18 m at Lewis, and 0.25 m at Crawfordsville and Nashua. The RCC seeding dates were from 25 September to 9 October with RCC-FS and from 17 September to 29 October with RCC-FC (Table 2). The RCC was terminated with application of 1 to 2 kg a.i. ha⁻¹ of glyphosate [N-(phosphonomethyl) glycine], between 19 April and 3 May with RCC-FS, and between 28 April and 10 May with RCC-FC. The overall project intent was to allow time for RCC growth, but terminate the RCC in a timely basis to avoid delay in annual crop planting. Therefore, as weather and soil conditions allowed, the RCC was terminated at least 1 wk before corn planting, and soybean planting at or within 1 wk after RCC termination.

Soil Sampling and Analysis

Soil was sampled by hand for profile NO₃-N determination with a 0.02 m diam. soil probe in fall 2009 and 2010 (0 to 0.9 m in 0.3-m increments) after soybean and corn harvest and before or at RCC seeding. Soil sampling after soybean harvest in 2009 was by block (RCC main plot) because no fertilizer N rate treatments had yet been applied to the prior-year corn, with six cores collected from each plot at 0.2 m away from one of the center soybean rows. In 2010, sampling following soybean was in prior-year corn plots that received 0N, 135N, and 225N, with six cores collected per plot in a diagonal pattern across two soybean rows, with one core from each row and a core 0.2 m from the side of each row. As there was

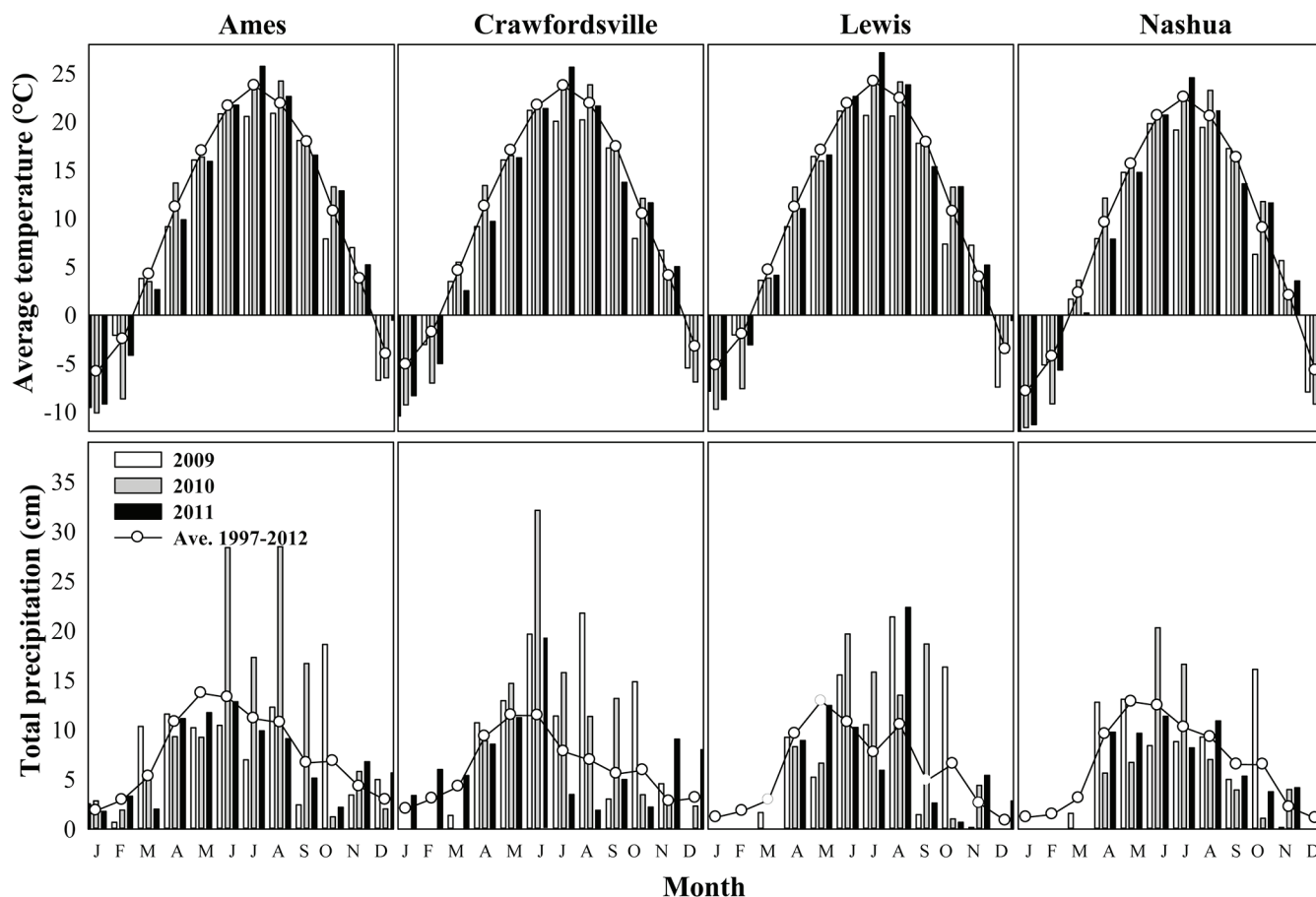


Fig. 1. Monthly mean temperature and total precipitation by site and year (data from Arritt and Herzmann, 2013).

no difference in $\text{NO}_3\text{-N}$ due to the prior-year N rates applied to corn, and in the first year there were no prior N-rates, soil profile $\text{NO}_3\text{-N}$ following soybean is presented across N rates. Sampling after corn harvest was in each plot that received N the prior spring, with six cores collected per plot in the diagonal pattern across two corn rows. Soil cores were mixed and a subsample saved for analysis. Collected soil was dried in a forced-air oven at 25°C , ground to pass a 2-mm sieve, and $\text{NO}_3\text{-N}$ determined by 2 mol L^{-1} KCl extraction and colorimetric Cd reduction using a Lachat flow injection analyzer (QuikChem 8500 Series 2, Lachat Instruments, Loveland, CO; Brown, 1998). Concentrations were converted to a mass basis, using a common bulk density of 1.3 g cm^{-3} for Iowa soils (Al-Kaisi et al., 2005; Pantoja et al., 2015), and added across depths to obtain the total soil $\text{NO}_3\text{-N}$ to a 0.9-m depth. The $\text{NO}_3\text{-N}$ amount in the subsoil could be underestimated by using the same soil bulk density since the top-layer bulk density tends to be lower.

Rye Biomass Sampling and Analysis

To determine aboveground BP and accumulated C and N, in the spring within 3 d before RCC termination (Table 2, considered time zero) aboveground RCC biomass at six random locations was sampled using a 0.093-m^2 PVC square frame that encompassed two RCC rows (amount per area basis adjusted for rye row spacing). The RCC plants were cut at the soil surface from within the frame and composited from the six locations into one sample. With the RCC-FS, biomass sampling was conducted by replicate because no N was applied to soybean, whereas with RCC-FC sampling was by each plot that received 0N, 135N, and 225N.

Additional RCC biomass was collected from each replicate (RCC-FS) or plot (RCC-FC) and split into three subsamples, fresh weight recorded, placed into nylon mesh bags (bag size was 40 by 30 cm and mesh size 3 by 1 mm), and the bags placed on the no-till surface in the middle of corresponding prior-year soybean or corn plots and between RCC rows. The mesh bags were not mixed or covered with crop residue. The RCC material was cut at the soil surface and placed intact into the mesh bags. At the same time, RCC subsamples were saved for DM determination and C and N analysis. The RCC biomass amount placed into the mesh bags varied depending on the BP amount at each site-year, but was intended to be 100 to 300 g of fresh RCC biomass in each bag. The mesh bags covered on average 0.06 m^2

when placed on the no-till soil surface. Placement was away from farm equipment traffic patterns to avoid damage during planting of corn or soybean and N application to corn. One set of bags was collected at 21, 63, and 105 d. In a few cases some soil was mixed with the RCC biomass sample, but was carefully removed by hand before weighing. The RCC biomass samples collected at time zero, and the remaining RCC biomass in each mesh bag at each sampling time, were dried in a forced-air oven at 60°C and weighed to estimate the BP (at time zero) and the remaining RCC biomass amount at each sampling time (hereafter the BP and the RCC biomass remaining are expressed on a DM basis). The initial RCC biomass amount measured at time zero was adjusted to an area basis for RCC row spacing, and that amount per unit area was used for BD determination after time zero.

All samples, including those collected at time zero, were ground to pass a 2-mm sieve and a subsample analyzed for total C and N by dry combustion (LECO CHN-2000 analyzer, LECO Corp., St. Joseph, MI; Nelson and Sommers, 1982). The amount of remaining RCC biomass, carbon in the rye cover crop biomass (RCC-C), and nitrogen in the rye cover crop biomass (RCC-N) at each sampling time was calculated on an area basis by relating the fraction that remained in the mesh bag to the amount per unit area determined at time zero. The C/N ratio of all RCC biomass samples was calculated by dividing the C amount by the N amount on an area basis.

Statistical Analysis

Statistical analyses of measured parameters were performed with PROC MIXED (SAS Institute, 2009), with an RCB split-plot design for N rate with RCC-FC. Blocks and years were considered random. For RCC-FS, analyses were only performed between sites. For the analyses of soil profile $\text{NO}_3\text{-N}$, BP, C, N, and C/N ratio in the RCC biomass, site was considered fixed for RCC-FS and RCC-FC, and N rate applied to the prior-year corn was considered fixed for RCC-FC. For the analysis of BD, RCC-C, RCC-N, and C/N ratio in the remaining RCC biomass, sampling time was a fixed factor. Differences between treatment means were assessed with the PDIF option in PROC MIXED and considered significant at $P \leq 0.05$.

The relationship between C/N ratio and N concentration of the RCC biomass at time zero and across sites and years was fit to the power regression model Eq. [1] using PROC NLIN. The

Table 2. Calendar dates for rye cover crop (RCC) seeding and biomass sampling.

Prior crop	Ames	Crawfordsville	Lewis	Nashua
RCC seeding				
Fall 2009				
Soybean	25 Sept.	29 Sept.	25 Sept.	9 Oct.
Corn	9 Oct.	30 Sept.	13 Oct.	29 Oct.
Fall 2010				
Soybean	5 Oct.	1 Oct.	30 Sept.	7 Oct.
Corn	5 Oct.	17 Sept.	30 Sept.	7 Oct.
RCC biomass sampling				
2010				
Soybean	21 Apr.	19 Apr.	22 Apr.	23 Apr.
Corn	28 Apr.	9 May	29 Apr.	4 May
2011				
Soybean	29 Apr.	29 Apr.	20 Apr.	28 Apr.
Corn	8 May	6 May	5 May	7 May

exponential decay regression model Eq. [2] was also fit using PROC NLIN for BD, RCC-C, and RCC-N as proposed by Collins et al. (1990). The exponential model fit was by site for RCC-FS, by site and fertilizer N rate applied to the prior-year corn for RCC-FC, and across sites and years for both RCC-FS and RCC-FC. PROC REG was used to fit the quadratic decay model for the C/N ratio of remaining RCC biomass (Eq. [3]) across sites and years. The coefficient of determination (R^2) for each model was calculated, and models were deemed significant at $P \leq 0.05$.

$$Y = ax^b \quad [1]$$

$$Y_t = Y_0 e^{-kt} \quad [2]$$

$$Y = a + bx + cx^2 \quad [3]$$

In the power regression model, Y represents the predicted N concentration (g N kg^{-1}), x is the C/N ratio in the RCC biomass, and a and b are constants of the model. In the exponential decay model, Y_t is the remaining RCC biomass, RCC-C, or RCC-N (kg ha^{-1}) at time t (d); Y_0 is the predicted initial RCC biomass, RCC-C, or RCC-N (kg ha^{-1}) at $t = 0$; e is the exponential constant with an approximate numerical value of 2.7182; and k is the relative decomposition rate coefficient ($\text{g g}^{-1} \text{d}^{-1}$). The parameters of the power and exponential models were considered significant if the 95% confidence intervals did not encompass zero (Ruffo and Bollero, 2003a). In the quadratic model, Y represents the predicted C/N ratio in the remaining RCC biomass, x is time (d), and a , b , and c are the intercept, linear coefficient, and quadratic coefficient of the regression model, respectively. The quadratic models were significant ($P \leq 0.05$) with an $R^2 = 1.0$.

An analysis of variance across years was used to investigate significance of site for RCC-FS and site and fertilizer N rate applied to the prior-year corn for RCC-FC for estimated amount of initial (Y_0) RCC biomass, RCC-C, and RCC-N, and relative decomposition rate coefficient (k) for RCC-BD, RCC-C, and RCC-N. Since k was not affected by site or interaction with N rate, model results were also summarized across sites and years.

Table 3. Post-soybean harvest 0.9-m soil depth profile $\text{NO}_3\text{-N}$ before rye cover crop seeding, across 2009 and 2010.

Site	$\text{NO}_3\text{-N}$ kg ha^{-1}
Ames	23c†
Crawfordsville	32b
Lewis	42a
Nashua	27bc
Mean	31

† Means with the same letter are not different ($P \leq 0.05$).

Table 4. Post-corn harvest 0.9-m soil depth profile $\text{NO}_3\text{-N}$ before rye cover crop seeding, across 2009 and 2010.

N rate†	Ames	Crawfordsville	Lewis	Nashua	Mean
	$\text{kg NO}_3\text{-N ha}^{-1}$				
0N	16a‡	23b	23b	24c	22c
135N	19a	22b	29ab	39b	27b
225N	18a	35a	33a	53a	35a
Mean	18C‡	27B	28B	38A	

† 0N, 135N, and 225N represent 0, 135, and 225 kg N ha^{-1} applied to the corn.

‡ Means with the same lowercase letter within a column and means by site across N rates with the same capital letter are not different ($P \leq 0.05$).

RESULTS AND DISCUSSION

Post-Harvest Soil Nitrate

Soil profile $\text{NO}_3\text{-N}$ in the top 0.9 m of soil after soybean and corn harvest was $<54 \text{ kg N ha}^{-1}$ at all sites, with most instances being much less than that amount (Tables 3 and 4). Soil profile $\text{NO}_3\text{-N}$ after soybean harvest was lowest at Ames and greatest at Lewis. After corn harvest and across N rates applied to corn, $\text{NO}_3\text{-N}$ was lowest at Ames and greatest at Nashua. Except for Ames, fertilizer N application resulted in a small increase in soil profile $\text{NO}_3\text{-N}$ with across site 135N and 225N application increasing soil $\text{NO}_3\text{-N}$ by only 5 and 13 kg N ha^{-1} compared to 0N, respectively. Corn grain yield in the overall project for 2009 and 2010 was high ($>12 \text{ Mg ha}^{-1}$) with adequate N application, as well as high soybean yield ($>4 \text{ Mg ha}^{-1}$). The high corn and soybean yields, in conjunction with above average growing season precipitation each year, and above average precipitation in October 2009 (Fig. 1), resulted in low soil profile $\text{NO}_3\text{-N}$ even with the 225N rate. The low soil profile $\text{NO}_3\text{-N}$ would be an indication that soil supply of plant available N to promote BP and N uptake was low. However, since the N rate applied to corn increased post-harvest soil profile $\text{NO}_3\text{-N}$, at sites except Ames, that increase would potentially influence BP and N uptake.

Rye Cover Crop Biomass Production and Nitrogen Accumulation

Rye Cover Crop Biomass Production

The average air temperature during early spring (March and April) in 2010 was 2°C warmer than the historical average at all sites, whereas 2011 was 2°C colder at three of the four sites. During that period, Ames was drier than the historical average in 2011, Crawfordsville was drier in 2010, and Lewis and Nashua did not receive any precipitation in March both years (Fig. 1).

The BP with RCC-FS and RCC-FC (across N rates applied to the prior-year corn) was greatest at Crawfordsville and lowest at Nashua (Tables 5 and 6, respectively). Crawfordsville was one of the southern sites, therefore, greater BP would be expected at that site. Nashua, however, was the most northern site and thus had a shorter spring period for RCC growth. According to Hoorman et al. (2009), BP in the early spring will be less in cooler climatic regions compared to temperate regions, along with factors such as residue cover, that result in lower soil temperature. On average, BP with RCC-FS was 10% ($100 \text{ kg DM ha}^{-1}$) less than RCC-FC (across N rates applied to the prior-year corn; Tables 5 and 6). Another factor affecting RCC growth was time of termination. The RCC-FS was terminated on average 2 wk before termination of the RCC-FC, with the earlier termination following soybean an attempt to reduce negative effects of RCC on the subsequent corn crop and to allow timely corn planting; with corn planting on average 1 wk before soybean.

Table 5. Aboveground rye cover crop biomass production (BP), C, N, and C/N ratio following soybean at the time of sampling in the spring, across 2010 and 2011.

Site	BP†	Total C	Total N	C/N
		kg ha ⁻¹		
Ames	1130ab‡	455ab	30a	14b
Crawfordsville	1230a	505a	29a	17a
Lewis	910ab	370ab	27a	13bc
Nashua	710b	285b	23a	12c
Mean	990	405	27	14

† Dry matter basis.

‡ Means with the same letter within a column are not different ($P \leq 0.05$).

Despite the lack of increased soil profile $\text{NO}_3\text{-N}$ with N application at Ames, the application of 225N to the prior-year corn did result in BP increase (170 kg DM ha⁻¹) compared to 0N (Table 6). At Lewis, there was increased soil profile $\text{NO}_3\text{-N}$, but no difference in BP with the prior-year N rate. At no site was there greater BP with the prior-year 135N rate compared to 0N. Although post-harvest soil profile $\text{NO}_3\text{-N}$ was increased with N applied to the prior-year corn at most sites, the increases were small compared to no-N application, and therefore BP was not greatly increased from that soil profile $\text{NO}_3\text{-N}$. Across sites and years, application of 225N increased BP by 32% (310 kg DM ha⁻¹) compared to 0N and by 26% (260 kg DM ha⁻¹) compared to 135N.

The BP was low compared to studies conducted by Ruffo and Bollero (2003a) in the Midwest, where BP was >3000 kg ha⁻¹. Reasons for low RCC-BP in this study included late seeding in the fall after soybean and corn harvest, cold temperatures in late fall, short spring period for RCC growth, and low post-harvest soil profile $\text{NO}_3\text{-N}$. Brennan et al. (2011) found that RCC-BP was also a function of site location and plant density.

Aboveground Rye Cover Crop Biomass Carbon and Nitrogen

As has been reported in previous research (Vigil and Kissel, 1991; Brennan et al., 2013), aboveground C in the RCC-FS and RCC-FC followed the same trend as BP. The C amount in the RCC-FS was greatest at Crawfordsville and lowest at Nashua, but the aboveground N amount was not different among sites (Table 5). Carbon in the RCC-FC was greatest at Crawfordsville and lowest at Nashua (Table 6). Carbon increased with the 225N applied to the prior-year corn only at those two sites, which differed from the BP which was also increased with the 225N rate at Ames. Nitrogen amount in the RCC-FC was also greatest at Crawfordsville and lowest at Nashua. The RCC-N amount was increased with N applied to the prior year corn at all sites except Lewis, which followed the BP and RCC-C trend. At no site did the 135N rate result in more RCC-FC C or N than with 0N (Table 6).

Across sites and years, application of 225N increased RCC-C by 30% (120 kg C ha⁻¹) and RCC-N by 40% (8 kg N ha⁻¹) in the RCC-FC compared to 0N and 135N (Table 6). The increase in rye N amount following corn N fertilization reflected the difference in residual soil $\text{NO}_3\text{-N}$ in the fall after corn harvest (8 to 13 kg $\text{NO}_3\text{-N}$ ha⁻¹). According to Sainju et al. (2005), RCC is capable of scavenging residual N to a 1.2-m depth. Our results showed that RCC-FC was influenced by post-harvest soil profile $\text{NO}_3\text{-N}$ from the 225N rate; however, the 135N rate apparently did not have enough post-harvest soil profile $\text{NO}_3\text{-N}$ increase to affect RCC growth and N uptake. Ranells and Waggener (1997) conducted a 2-yr experiment to evaluate N uptake by corn and RCC recovery of residual N with ¹⁵N-labeled fertilizer. They applied 200 kg N ha⁻¹ to the corn crop and found that corn together with RCC utilized 75% of the fertilizer N, and RCC recovered 39% of the residual fertilizer N.

Table 6. Aboveground rye cover crop biomass production (BP), C, N, and C/N ratio following corn at the time of sampling in the spring, across 2010 and 2011.

N rate†	Ames	Crawfordsville	Lewis	Nashua	Mean
		BP‡, kg ha ⁻¹			
0N	760b§	1920b	700a	500b	970b
135N	770b	2130b	690a	510b	1020b
225N	930a	2910a	560a	710a	1280a
Mean	820B§	2320A	650BC	570C	
		RCC-C, kg C ha ⁻¹			
0N	310a	800b	285a	205b	400b
135N	315a	885b	280a	205b	420b
225N	385a	1220a	235a	290a	530a
Mean	335B	970A	265BC	235C	
		RCC-N, kg ha ⁻¹			
0N	16b	28b	15a	12b	18b
135N	18ab	31b	16a	13b	19b
225N	25a	44a	15a	20a	26a
Mean	19B	34A	16BC	15C	
		C/N ratio			
0N	20a	29a	19a	17a	21a
135N	18b	29a	18a	15b	20b
225N	16c	28a	15b	14b	18c
Mean	18B	28A	17BC	15C	

† 0N, 135N, and 225N represent 0, 135, and 225 kg N ha⁻¹ applied to the prior-year corn.

‡ Dry matter basis.

§ Means with the same lowercase letter within a column and measurement, and across N rate means by site with the same capital letter within a measurement, are not different ($P \leq 0.05$).

Accumulation of N in the RCC reflected the low soil $\text{NO}_3\text{-N}$ in both RCC-FS and RCC-FC systems. Without considering soil N mineralization in the fall after soil profile sampling and in the early spring until the time of RCC termination (due to cold temperatures during that period which limits mineralization), or leaching below the RCC root zone, the inorganic soil N amount available for RCC uptake would approximate the post-harvest soil profile $\text{NO}_3\text{-N}$. Based on the RCC-N uptake, the RCC accumulated an average 87 and 75% of the post-harvest soil profile $\text{NO}_3\text{-N}$, respectively, with RCC-FS and RCC-FC.

Rye Cover Crop Biomass Carbon/Nitrogen Ratio

The C/N ratio in the RCC biomass increased slightly with the corresponding greater BP with both RCC-FS and RCC-FC, but decreased with N rate applied to the prior-year corn with RCC-FC at three sites (not Crawfordsville) and the mean across sites (Tables 5 and 6). According to Brennan et al. (2013), the C/N ratio increased through the RCC growth period and with increasing BP. The BP at Crawfordsville was three to four times greater than the other sites, and had the highest C/N ratio, which may have resulted in the lack of C/N difference with N application to the prior-year corn at that site. Across sites and years, the C/N ratio was lower with RCC-FS than RCC-FC, a reflection of the less limited N supply in the RCC-FS system and the shorter spring period for RCC-FS to grow.

Across sites and years, C concentration in the RCC biomass (data not shown) was the same with RCC-FS and RCC-FC with 0N and 135N (average 410 g C kg^{-1}); however, application of 225N to the prior-year corn increased C concentration by 7 g C kg^{-1} ($P < 0.001$). Across sites and years, N concentration in the RCC biomass (data not shown) was 8 g N kg^{-1} greater with RCC-FS than RCC-FC across N rates applied to the prior-year corn (31 vs. 23 g N kg^{-1}), and 10 g N kg^{-1} greater with RCC-FS when compared to RCC-FC with 0N. Nitrogen application to the prior-year corn increased N concentration in the RCC biomass,

and was 21, 23, and 25 g N kg^{-1} for 0N, 135N, and 225N, respectively ($P < 0.001$). According to Schomberg et al. (1994), both C and N accumulation affects crop biomass quality (that is, the C/N ratio), and Douglas and Rickman (1992) found that N concentration in crop biomass plays an important role in biomass degradation and N cycling. Vigil and Kissel (1991) found that despite an increase in crop biomass amount, C concentration was fairly constant during the growing season, but not the C/N ratio. Our results showed that C concentration was similar with RCC-FS and RCC-FC; however, N concentration was different depending on the prior-crop and N rate applied to the prior-year corn.

As expected the C/N ratio in the RCC biomass increased with decreasing rye N concentration, and was lower with RCC-FS than RCC-FC (Fig. 2). The lower C/N ratio and greater N concentration in the RCC-FS also confirmed that RCC was less N-limited or less influenced by the prior-crop than the RCC-FC. The high R^2 of the relationship indicates that varying N concentration was the factor determining the C/N ratio of RCC biomass. The relationship between C/N ratio and N concentration observed in this study was previously reported by Vigil and Kissel (1991) and confirmed by Brennan et al. (2013); where they found that up to 75% of the N mineralized with crop biomass degradation could be explained by the biomass C/N ratio. According to Brennan et al. (2013), the C/N ratio of RCC biomass can be estimated readily by N concentration due to the narrow spread of C concentration. This relationship could be useful for estimating the C or BP amount added to soil from an RCC, thus only needing the RCC biomass N concentration measurement.

Rye Cover Crop Biomass Degradation and Nitrogen Recycling

The period from late April to early August (time period of the study) in 2010 was 1°C warmer than the historical average at all sites and there was more precipitation than the historical average each month, especially with high precipitation in June

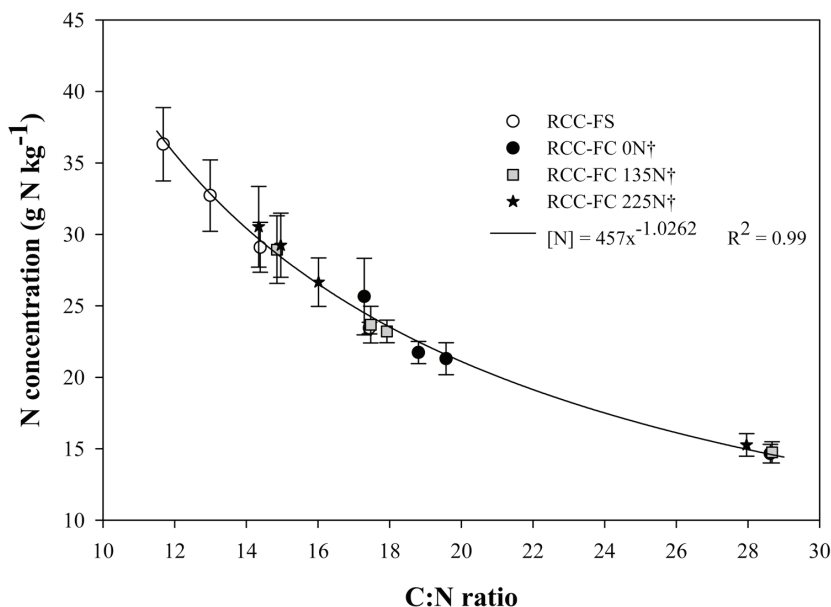


Fig. 2. Relationship between the rye cover crop (RCC) biomass C/N ratio and N concentration at the time of RCC sampling following soybean (RCC-FS) and RCC following corn (RCC-FC). Data points are the mean of each RCC system for each site across years. Bars represent the standard error. The regression line was significant ($P < 0.001$). †0N, 135N, and 225N stand for 0, 135, and 225 kg N ha⁻¹ applied to the prior-year corn.

Table 7. Analysis of variance for rye cover crop (RCC) biomass degradation (BD), carbon in the rye cover crop biomass (RCC-C), nitrogen in the rye cover crop biomass (RCC-N), and C/N ratio with rye cover crop following soybean (RCC-FS) and RCC following corn (RCC-FC), across 2010 and 2011.

Source	RCC-BD	RCC-C	RCC-N	C/N
<i>P > F</i>				
RCC-FS				
Site (S)	0.131	0.086	0.195	0.048
Time (T)†	<0.001	<0.001	<0.001	<0.001
S × T	0.002	0.022	0.501	0.113
RCC-FC				
Site (S)	<0.001	<0.001	<0.001	<0.001
Time (T)	<0.001	<0.001	<0.001	<0.001
S × T	<0.001	<0.001	0.174	<0.001
N rate (NR)‡	<0.001	<0.001	<0.001	<0.001
S × NR	<0.001	<0.001	<0.001	0.665
T × NR	0.160	0.129	0.057	0.013
S × T × NR	0.360	0.470	0.875	0.671

† Mesh bag collection day after placement.

‡ Nitrogen rate applied to the prior-year corn.

Table 8. Exponential decay model parameters for rye cover crop (RCC) biomass degradation (BD), carbon in the rye cover crop biomass (RCC-C), and nitrogen in the rye cover crop biomass (RCC-N) for RCC following soybean as a function of mesh bag collection time after placement (d), across 2010 and 2011.

Site	BD				RCC-C				RCC-N			
	Y_0 †	k ‡	R^2	$P > F$	Y_0 †	k	R^2	$P > F$	Y_0 †	k	R^2	$P > F$
	kg ha ⁻¹	g g ⁻¹ d ⁻¹			kg ha ⁻¹	g g ⁻¹ d ⁻¹			kg ha ⁻¹	g g ⁻¹ d ⁻¹		
Ames	1110	-0.009	0.95	0.005	470	-0.018	0.98	0.005	31	-0.015	0.98	0.005
Crawfordsville	1220	-0.013	0.98	0.003	510	-0.016	0.98	0.004	29	-0.011	0.98	0.003
Lewis	920	-0.006	1.00	<0.001	385	-0.015	0.99	0.003	28	-0.015	0.99	0.003
Nashua	740	-0.010	0.96	0.005	295	-0.016	0.98	0.006	23	-0.016	0.99	0.002

† Y_0 , estimated initial RCC biomass dry matter, C, or N.

‡ k , relative decomposition rate coefficient.

and August at Ames and in June at Crawfordsville. In 2011, precipitation was near the historical average between late April to early August at all sites, but July and August were 2°C warmer compared to the historical average (Fig. 1).

With RCC-FS, the BD (measured as remaining biomass over time), RCC-C amount, and C/N ratio differed between site and sampling time (expressed in d) after mesh bag placement in the field (Table 7). However, the RCC-N amount was different only for sampling time (Table 7).

The BD and RCC-C amount with RCC-FC differed between site and time, and also between site and N rate applied to the prior-year corn. However, there was no site × time interaction for RCC-N amount (Table 7), but there was an interaction between site and N rate. There was no interaction between time and N rate, or three-way interaction, for BD, RCC-C, and RCC-N in the RCC-FC. Therefore, the BD, RCC-C, and RCC-N were the same for site and N rate across sampling time. The microbial use of available C for BD can result in potential N mineralization (Ruffo and Bollero, 2003a), and since N concentration is the driving factor for changes in the C/N ratio with BD (Vigil and Kissel, 1991), N recycling patterns and rates are not necessarily the same as for BD or C recycling.

The exponential decay model described the BD, RCC-C, and RCC-N across the 105-d period. Parameter estimates for the exponential decay models and statistics indicating the significance of the models for degradation of RCC-FS and RCC-FC at each site and across years are presented in Tables 8 and 9, respectively.

All models were developed with the means of remaining RCC biomass, RCC-C, and RCC-N by site with RCC-FS, and also by N rate applied to the prior-year corn with RCC-FC.

The exponential decay models for BD, RCC-C, and RCC-N with RCC-FS were significant ($P < 0.05$) for each site and had an $R^2 \geq 0.95$ (Table 8). The greatest initial RCC biomass (Y_0) was estimated at Crawfordsville and the lowest at Nashua, which matched the BP measured at time zero. Also, the relative BD rate (k) was greatest at Crawfordsville and lowest at Lewis. Despite similar annual temperature between the two sites, precipitation was greater at Crawfordsville than Lewis and the increased moisture may have resulted in a greater k for the Crawfordsville site. The decay models for RCC-C and RCC-N had estimated initial RCC-C and RCC-N amounts (Y_0) that matched the C and N amounts measured at time zero. However, differences in k between sites for RCC-C were smaller than for BD. The greatest fraction of RCC biomass remaining after 105 d with RCC-FS was at Lewis (52%) and the lowest at Crawfordsville (25%). The difference in BD remaining between the two sites was due to the different k value for each site. Ruffo and Bollero (2003a) found that by corn harvest, there was still 5% RCC biomass remaining on the soil surface, with the amount varying with initial BP and accumulated C.

As found with RCC-FS, all exponential decay models with RCC-FC for BD, RCC-C, and RCC-N were significant at each site for each N rate applied to the prior-year corn (Table 9). In all but two cases (BD and RCC-N with 0N at Ames), the R^2 was ≥ 0.90 . The Crawfordsville site has a poorly drained soil that saturates

Table 9. Exponential decay model parameters for rye cover crop (RCC) biomass degradation (BD), carbon in the rye cover crop biomass (RCC-C), and nitrogen in the rye cover crop biomass (RCC-N) for RCC following corn as a function of mesh bag collection time after placement (d), across 2010 and 2011.

Site and N rate†	BD				RCC-C				RCC-N			
	Y_0 ‡	k §	R^2	$P > F$	Y_0 ‡	k	R^2	$P > F$	Y_0 ‡	k	R^2	$P > F$
	kg ha ⁻¹	g g ⁻¹ d ⁻¹			kg ha ⁻¹	g g ⁻¹ d ⁻¹			kg ha ⁻¹	g g ⁻¹ d ⁻¹		
Ames												
0N	820	-0.009	0.89	0.014	335	-0.016	0.95	0.014	18	-0.012	0.88	0.025
135N	770	-0.006	1.00	<0.001	325	-0.013	0.98	0.003	18	-0.009	0.96	0.005
225N	990	-0.010	0.94	0.009	415	-0.015	0.93	0.017	27	-0.013	0.90	0.022
Crawfordsville												
0N	1950	-0.010	0.98	0.002	815	-0.011	0.98	0.002	28	-0.005	0.96	0.002
135N	2180	-0.011	0.98	0.003	910	-0.011	0.98	0.003	31	-0.005	0.97	0.001
225N	3010	-0.010	0.97	0.003	1270	-0.010	0.97	0.004	45	-0.004	0.93	0.002
Lewis												
0N	740	-0.010	0.94	0.008	305	-0.017	0.95	0.013	16	-0.014	0.93	0.015
135N	720	-0.010	0.96	0.005	300	-0.016	0.96	0.012	18	-0.014	0.92	0.019
225N	580	-0.007	0.96	0.003	250	-0.014	0.95	0.011	16	-0.013	0.93	0.014
Nashua												
0N	530	-0.009	0.95	0.006	215	-0.013	0.97	0.006	12	-0.011	0.95	0.007
135N	530	-0.011	0.98	0.003	215	-0.013	0.97	0.007	14	-0.011	0.99	0.002
225N	730	-0.012	0.99	0.002	300	-0.014	0.99	0.003	20	-0.013	1.00	<0.001

† 0N, 135N, and 225N represent 0, 135, and 225 kg N ha⁻¹ applied to the prior-year corn.

‡ Y_0 , estimated initial RCC biomass dry matter, C, or N.

§ k , relative decomposition rate coefficient.

Table 10. Analysis of variance for fixed effects of the estimated initial amount (Y_0) and relative decomposition rate (k) of exponential decay models for rye cover crop (RCC) biomass degradation (BD), carbon in the rye cover crop biomass (RCC-C), and nitrogen in the rye cover crop biomass (RCC-N) for rye cover crop following soybean (RCC-FS) and rye cover crop following corn (RCC-FC), across 2010 and 2011.

Fixed effects	Y_0 , kg ha ⁻¹			k , g g ⁻¹ d ⁻¹		
	BD	RCC-C	RCC-N	BD	RCC-C	RCC-N
	$P > F$					
			RCC-FS			
Site	0.704	0.669	0.826	0.336	0.767	0.348
			RCC-FC			
Site	0.009	0.012	0.020	0.614	0.206	0.219
N rate†	0.097	0.107	0.090	0.519	0.177	0.760
Site × N rate	0.042	0.037	0.393	0.706	0.341	0.469

† Nitrogen rate applied to the prior-year corn.

relatively quickly with high precipitation. The potential for excess soil moisture would add variability, which could affect BD and N recycling. The greatest initial RCC biomass (Y_0) was estimated at Crawfordsville and the lowest at Nashua, which matched the BP measured at time zero. The k for BD was within a narrow range (-0.012 to -0.006 g g⁻¹ d⁻¹) across sites, indicating that BD rate with RCC-FC was similar across sites and N rates applied to the prior-year corn. The RCC-C and RCC-N decay models showed that estimated initial RCC-C and RCC-N amount (Y_0) matched the C and N amounts measured at time zero. The range for k with RCC-C and RCC-N was narrow (-0.017 to -0.010 g g⁻¹ d⁻¹ for RCC-C, and -0.014 to -0.004 g g⁻¹ d⁻¹ for RCC-N). The k for RCC-C with RCC-FC was similar to that for RCC-C with RCC-FS, indicating that C recycling over time was similar for both RCC-FC and RCC-FS. However, k for RCC-N with RCC-FC was lower than that for RCC-N with RCC-FS, indicating that N recycling was slower with RCC-FC than RCC-FS. Overall, estimated k values were similar to those reported by Kaboneka et al. (1997), who conducted an incubation study evaluating corn, soybean, and wheat

(*Triticum aestivum* L.) biomass degradation over 30 d. They reported that decomposition ranged from 39% for wheat to 67% for soybean.

The significance level of the exponential decay models and R^2 for both RCC-FS and RCC-FC were high compared to a similar study conducted by Ruffo and Bollero (2003a) where they sampled RCC biomass that remained as-is on the soil surface across plots over time. In this study, the models goodness of fit was likely improved due to placement of the RCC biomass into mesh bags and allocation on the soil surface away from farm equipment traffic patterns, which avoided RCC biomass damage from plot activities. The placement of RCC biomass into soil (buried vs. soil surface and into mesh bags) could also create significant changes in k , as crop residues incorporated to the soil degrade faster than those remaining on the soil surface (Douglas and Rickman, 1992). Our study was conducted in a no-till system, and this could have resulted in slower BD compared to that in a tilled system with greater soil contact.

Site did not have an influence on Y_0 or k for BD, RCC-C, and RCC-N with RCC-FS (Table 10). With RCC-FC, the

interaction between site and N rate applied to the prior-year corn influenced Y_0 for BD and RCC-C, but not RCC-N. The k value was not influenced by any factor with RCC-FC. Therefore, the net BD and N recycling amount depended on Y_0 , but not k , and the N recycling was the same across sites and N rates applied to the prior-year corn. The exponential decay models across sites and years for BD, RCC-C, and RCC-N with RCC-FS and RCC-FC are shown in Fig. 3. Across sites and years, after 105 d 38% of the RCC biomass with RCC-FS and RCC-FC (across N rates applied to the prior-year corn) still remained. The N recycling of accumulated N (that not remaining in the mesh bag) with RCC-FS (N for the subsequent corn crop) was 25% (7 kg N ha⁻¹), 60% (16 kg N ha⁻¹), and 80% (22 kg N ha⁻¹) by 21, 63,

and 105 d, respectively, after time zero. Comparatively, by the end of the 105-d period and across N rates applied to the prior-year corn, 64% (14 kg N ha⁻¹) of accumulated N with RCC-FC (N for the subsequent soybean crop) was recycled.

The total N recycled was low with both RCC-FS and RCC-FC, which reflected the low N accumulation in the RCC biomass. Ruffo and Bollero (2003b) found that slow nutrient recycling rates are associated not only with accumulation of high C and low N containing compounds, but also with C and N availability for microbial use in RCC-BD and nutrient recycling. This can be especially important with cereal crops (with high C/N ratio), as with an RCC, compared to legumes. Early cover crop termination results in lower C/N ratios due to the shorter time to accumulate

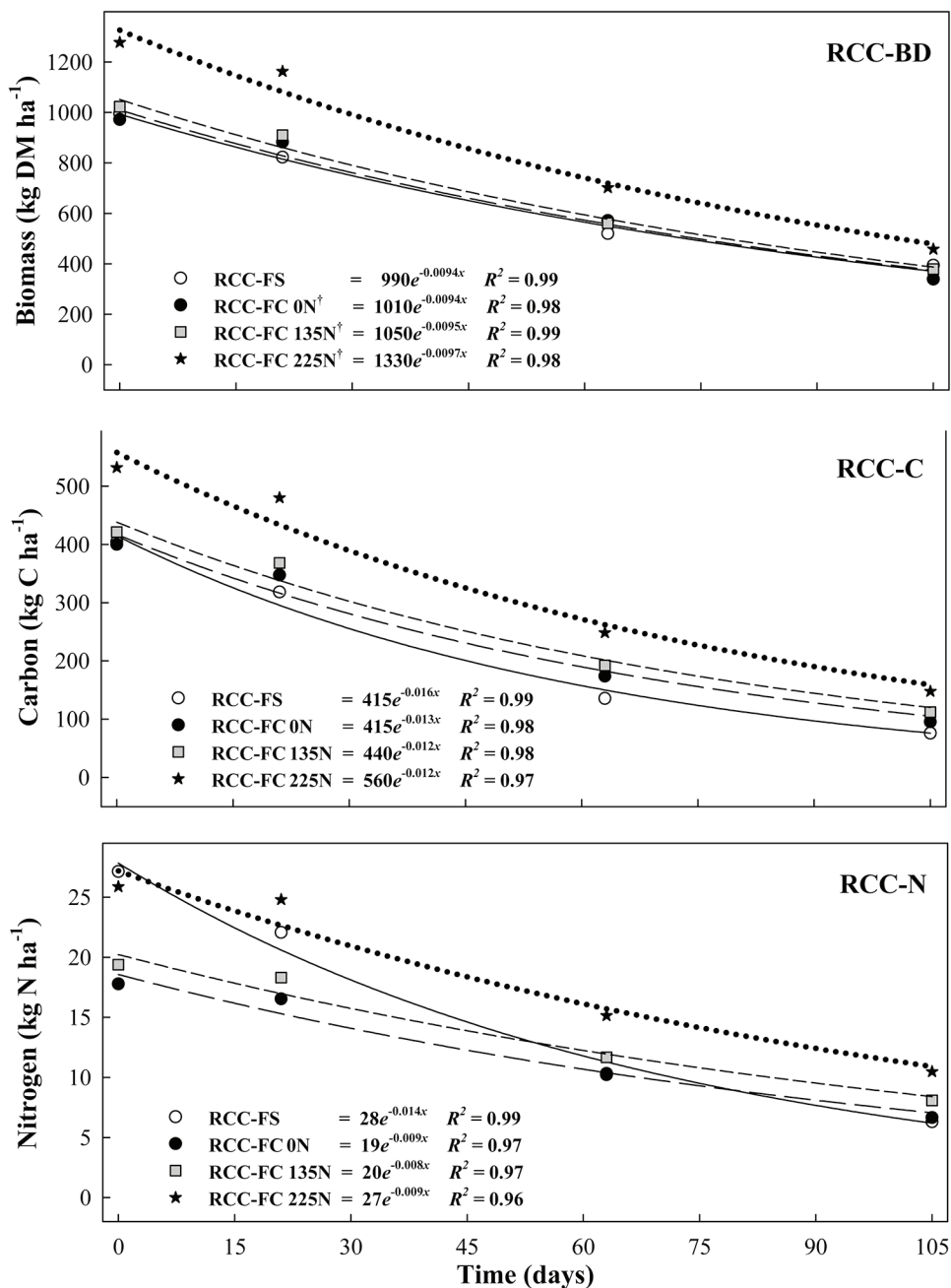


Fig. 3. Exponential decay models as a function of time for rye cover crop (RCC) biomass degradation (BD), carbon in the rye cover crop biomass (RCC-C), and nitrogen in the rye cover crop biomass (RCC-N) with rye cover crop following soybean (RCC-FS) and rye cover crop following corn (RCC-FC). Data points are the mean of each RCC system across sites and years. All regression models were significant ($P \leq 0.05$). [†] 0N, 135N, and 225N stand for 0, 135, and 225 kg N ha⁻¹ applied to the prior-year corn.

cellulose, hemicellulose, and lignin (Kaspar and Singer, 2011). The more rapid N recycling with RCC-FS could have been a result of the lower initial C/N ratio in the RCC biomass compared with RCC-FC (Tables 5 and 6, Fig. 4). The RCC-FS was terminated 2 wk before termination of RCC-FC, and hence had less time to grow and accumulate high C/N ratio compounds, which resulted in a more rapid and greater N recycling. The difference in RCC termination date is also reflected in the lower C/N ratio over time (Fig. 4). The prior-year corn with 225N rate resulted in a lower initial C/N ratio compared to 0N, but since the difference was small, N recycling was similar with and without N application to the prior-year corn. As the rate of C and N recycling decreased over time, the C/N ratio became the same with RCC-FS and RCC-FC (Fig. 4), an indication of the low N amount and high C/N compounds in remaining RCC biomass.

Results of this study suggest that residual $\text{NO}_3\text{-N}$ from fertilizer N applied to prior-year corn has potential to increase BP and N uptake, but not the rate of BD, C or N recycling. Nitrogen recycling amount from RCC-FS was small compared to agronomic N application rates and would have minimal impact on soil potential supply of plant available N for the subsequent corn crop and reduction in corn N requirement. Ruffo and Bollero (2003a) conducted a study in Illinois to evaluate RCC-BD and found that 4 to 6 wk after corn emergence the BD recycled only 33% of the accumulated N in the RCC biomass within the system. They concluded that BD and nutrient recycling are more useful in soil conservation and soil N storage than as an available N source for corn. Using surface-applied ^{15}N -labeled RCC biomass, Ranells and Wagger (1997) found that corn recovered 4% of N recycled from BD. Garwood et al. (1999) found that an RCC increased soil inorganic N by a total of 160 kg N ha^{-1} across an 8-yr study, and concluded that the increase in soil N storage was due to less $\text{NO}_3\text{-N}$ loss in tile drainage water than N accumulation in the RCC biomass. Kuo and Jellum (2000) indicated that an increase in soil N is possible, but in soils with high background levels of soil organic matter, it is difficult to measure that increase with implementation of new crop management practices such as use of an RCC. That could be the case in Iowa

soils which have high soil organic matter levels. In another study, Kuo and Jellum (2002) concluded that an RCC did not reduce presidedress soil $\text{NO}_3\text{-N}$ concentrations compared to fallow and that corn yield was mostly affected by initial soil profile $\text{NO}_3\text{-N}$ amount and N rate. Our results in this rye degradation study, along with a lack of change in the corn economic optimum N rate with use of the RCC system found in the overall multi-year project (Pantoja et al., 2015), confirmed that the RCC system recycled a low amount of N and would have a minimal effect on the supply of plant available N to the corn crop.

CONCLUSIONS

Across sites and years, BP and N uptake were low due to low post-harvest soil profile $\text{NO}_3\text{-N}$ and the short spring period for RCC growth. Low temperatures in late fall and early spring, and years with above normal precipitation, could have also resulted in the low soil profile $\text{NO}_3\text{-N}$ and low BP. Based on soil profile $\text{NO}_3\text{-N}$ present after annual crop harvest, the RCC accumulated 87 and 75% of the soil profile N with RCC-FS and RCC-FC, respectively. There were differences in BP, RCC-C, and RCC-N among sites with RCC-FS, and also among fertilizer N rates applied to the prior-year corn with RCC-FC, but differences were small. With RCC-FC, N applied to corn at 225N resulted in the greatest BP (mean $1280 \text{ kg DM ha}^{-1}$) and accumulated N (26 kg N ha^{-1}), a total N amount similar to that with RCC-FS (27 kg N ha^{-1}). However, accumulated N was greater with RCC-FS than with RCC-FC with 0N and 150N (18 kg N ha^{-1}), a reflection of the different prior-crop and seeding date.

The relative decomposition rate coefficients (k) in the exponential decay models for BD and RCC-C were similar with RCC-FS and RCC-FC, and for the different N rates applied to the prior-year corn. However, decay models had a greater degradation rate for RCC-N with RCC-FS than RCC-FC. The low BP and N uptake, in combination with the relatively slow BD rate, resulted in a low RCC N recycling amount in all cases. After 105 d, 22 kg N ha^{-1} (80% of uptake) was recycled with RCC-FS while only 14 kg N ha^{-1} (64% of uptake across N rates applied to the prior-year corn) was recycled with RCC-FC. The more rapid

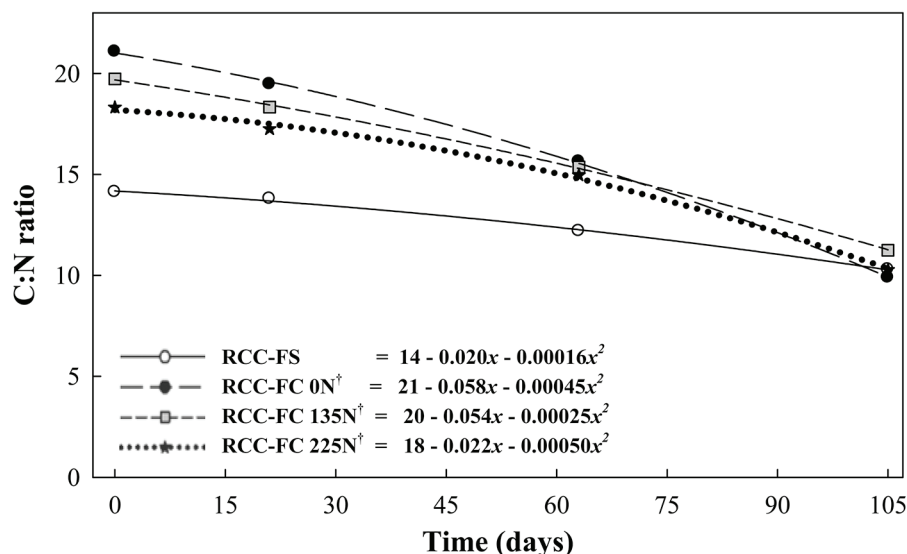


Fig. 4. Relationship as a function of time for C/N ratio change with rye cover crop (RCC) biomass degradation (BD) with rye cover crop following soybean (RCC-FS) and rye cover crop following corn (RCC-FC). Data points are the mean of each RCC system across sites and years. † 0N, 135N, and 225N stand for 0, 135, and 225 kg N ha^{-1} applied to the prior-year corn.

and greater N recycling with RCC-FS compared to RCC-FC appeared to be associated with a lower initial RCC C/N ratio.

Rye cover crops can be a good management practice for several environmental purposes, such as reduced $\text{NO}_3\text{-N}$ loss to water systems and erosion control. However, the RCC system in this study did not accumulate an agronomically meaningful amount of N to recycle, and in conjunction with slow degradation, would limit the potential to reliably provide substantial amount of N to the following soybean or corn crop. Additional research is needed to develop cover crop management recommendations that enhance N uptake and recycling as well as increase row crop performance.

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REFERENCES

- Acuña, J.C.M., and M.B. Villamil. 2014. Short-term effects of cover crops and compaction on soil properties and soybean production in Illinois. *Agron. J.* 106:860–870. doi:10.2134/agronj13.0370
- Al-Kaisi, M.M., X. Yin, and M.A. Licht. 2005. Soil carbon and nitrogen changes as affected by tillage system and crop biomass in a corn–soybean rotation. *Appl. Soil Ecol.* 30:174–191. doi:10.1016/j.apsoil.2005.02.014
- Arritt, R.W., and D. Herzmann. 2013. Iowa environmental mesonet. Iowa State Univ., Ames. <http://mesonet.agron.iastate.edu/agclimate/hist/dailyRequest.php> (accessed 28 Jan. 2013).
- Bernstein, E.R., J.L. Posner, D.E. Stoltenberg, and J.L. Hedtcke. 2011. Organically managed no-tillage rye-soybean systems: Agronomic, economic, and environmental assessment. *Agron. J.* 103:1169–1179. doi:10.2134/agronj2010.0498
- Brennan, E.B., and N.S. Boyd. 2012. Winter cover crop seeding rate and variety affects during eight years of organic vegetables: III. Cover crop biomass production. *Agron. J.* 104:684–698. doi:10.2134/agronj2011.0330
- Brennan, E.B., N.S. Boyd, and R.F. Smith. 2013. Winter cover crop seeding rate and variety affects during eight years of organic vegetables: I. Cover crop residue quality and nitrogen mineralization. *Agron. J.* 105:171–182. doi:10.2134/agronj2012.0258
- Brennan, E.B., N.S. Boyd, R.F. Smith, and P. Foster. 2011. Comparison of rye and legume-rye cover crop mixtures for vegetable production in California. *Agron. J.* 103:449–463. doi:10.2134/agronj2010.0152
- Brown, J.R., editor. 1998. Recommended chemical soil test procedures for the North Central Region. North Central Reg. Res. Publ. no. 221 (Rev) SB 1001. Missouri Agric. Exp. Stn, Columbia.
- Cirilo, A.G., and F.H. Andrade. 1994. Sowing date and maize productivity: II. Kernel number determination. *Crop Sci.* 34:1044–1046. doi:10.2135/cropsci1994.0011183X003400040038x
- Collins, H.P., L.F. Elliott, R.W. Rickman, D.F. Bezdicsek, and R.I. Papendick. 1990. Decomposition and interactions among wheat residue components. *Soil Sci. Soc. Am. J.* 54:780–785. doi:10.2136/sssaj1990.03615995005400030026x
- Dabney, S.M., J.A. Delgado, J.J. Meisinger, H.H. Schomberg, M.A. Liebig, T. Kaspar et al. 2010. Using cover crops and cropping systems for nitrogen management. In: J.A. Delgado and R.F. Follett, editors, *Advances in nitrogen management for water quality*. Soil and Water Conserv. Soc., Ankeny, IA. p. 230–281.
- Dhima, K.V., I.B. Vasilakoglou, I.G. Eleftherohorinos, and A.S. Lithourgidis. 2006. Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. *Crop Sci.* 46:345–352. doi:10.2135/cropsci2005-0186
- Dimnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agron. J.* 94:153–171. doi:10.2134/agronj2002.0153
- Douglas, D.L., Jr., and R.W. Rickman. 1992. Estimating crop residue decomposition from air temperature, initial nitrogen content, and residue placement. *Soil Sci. Soc. Am. J.* 56:272–278. doi:10.2136/sssaj1992.03615995005600010042x
- Drury, C.F., C.S. Tan, T.W. Welacky, W.D. Reynolds, T.Q. Zhang, T.O. Oloya et al. 2014. Reducing nitrate loss in tile drainage water with cover crops and water-table management systems. *J. Environ. Qual.* 43:587–598. doi:10.2134/jeq2012.0495
- Duiker, S.W., and W.S. Curran. 2005. Rye cover crop management for corn production in the northern mid-Atlantic region. *Agron. J.* 97:1413–1418. doi:10.2134/agronj2004.0317
- Farsad, A., T.O. Randhir, S.J. Herbert, and M. Hashemi. 2011. Spatial modeling of critical planting date for winter rye cover crop to enhance nutrient recovery. *Agron. J.* 103:1252–1257. doi:10.2134/agronj2010.0433
- Feyereisen, G.W., B.N. Wilson, G.R. Sands, J.S. Strock, and P.M. Porter. 2006. Potential for a rye cover crop to reduce nitrate loss in southwestern Minnesota. *Agron. J.* 98:1416–1426. doi:10.2134/agronj2005.0134
- Franzluebbers, A.J. 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. *Soil Tillage Res.* 83:120–147. doi:10.1016/j.still.2005.02.012
- Garwood, T.W.D., D.B. Davies, and A.R. Hartley. 1999. The effect of winter cover crops on yield of following spring crops and nitrogen balance in a calcareous loam. *J. Agric. Sci.* 132:1–12. doi:10.1017/S0021859698006169
- Gregory, J.M., T.R. McCarty, F. Ghidry, and E.E. Alberts. 1985. Derivation and evaluation of a residue decay equation. *Trans. ASAE* 28:0098–0101. doi:10.13031/2013.32210
- Hoorman, J.J., R. Islam, A. Sundermeier, and R. Reeder. 2009. Using cover crops to convert to no-till. AEX-540-09. Ohio State Univ. Ext. Agric. and Natural Resources, Columbus.
- Iowa State University. 2014. Reducing nutrient loss: Science shows what works. Publ. SP 435. Iowa State Univ. Ext. and Outreach, Ames.
- Jacinthe, P.A., W.A. Dick, and L.C. Brown. 2000. Bioremediation of nitrate-contaminated shallow soils and waters via water table management techniques: Evolution and release of nitrous oxide. *Soil Biol. Biochem.* 32:371–382. doi:10.1016/S0038-0717(99)00163-7
- Johnson, T.J., T.C. Kaspar, K.A. Kohler, S.J. Corak, and S.D. Logsdon. 1998. Oat and rye overseeded into soybean as fall cover crops in the upper Midwest. *J. Soil Water Conserv.* 53:276–279.
- Kaboneka, S., W.E. Sabbe, and A. Mauromoustakos. 1997. Carbon decomposition kinetics and nitrogen mineralization from corn, soybean, and wheat residues. *Commun. Soil Sci. Plant Anal.* 28:1359–1373. doi:10.1080/00103629709369880
- Kaspar, T.C., D.B. Jaynes, T.B. Parkin, and T.B. Moorman. 2012. Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. *Agric. Water Manage.* 110:25–33.
- Kaspar, T.C., J.K. Radke, and J.M. Lafen. 2001. Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. *J. Soil Water Conserv.* 56:160–164.
- Kaspar, T.C., and J.W. Singer. 2011. The use of cover crops to manage soils. In: J.L. Hatfield and T.J. Sauer, editors, *Soil management: Building a stable base for agriculture*. SSSA, Madison, WI. p. 321–337. doi:10.2136/2011.soilmanagement.c21.

- Kramberger, B., A. Gselman, M. Janzekovic, M. Kaligalic, and B. Bracko. 2009. Effects of cover crops on soil mineral nitrogen and on the yield and nitrogen content of maize. *Eur. J. Agron.* 31:103–109. doi:10.1016/j.eja.2009.05.006
- Kuo, S., and E.M. Jellum. 2000. Long-term winter cover cropping effects on corn (*Zea mays* L.) production and soil nitrogen availability. *Biol. Fertil. Soils* 31:470–477. doi:10.1007/s003740000193
- Kuo, S., and E.M. Jellum. 2002. Influence of winter cover crop and residue management on soil nitrogen availability. *Agron. J.* 94:501–508. doi:10.2134/agronj2002.5010
- Lamarca, C.C. 1996. The management of no-till. In: C.C. Lamarca, editor, *Stubble over the soil. The vital role of plant residue in soil management to improve soil quality*. ASA, Madison, WI. p. 112–183.
- Lawlor, P.A., M.J. Helmers, J.L. Barker, S.W. Melvin, and D.W. Lemke. 2008. Nitrogen application rate effect on nitrate-nitrogen concentration and loss in subsurface drainage for a corn-soybean rotation. *Trans. ASABE* 51:83–94. doi:10.13031/2013.24229
- Ma, L., G.A. Peterson, L.R. Ahuja, L. Sherrod, M.J. Shaffer, and K. W. Rojas. 1999. Decomposition of surface crop residues in long-term studies of dryland agroecosystems. *Agron. J.* 91:401–409. doi:10.2134/agronj1999.00021962009100030008x
- McDaniel, M.D., L.K. Tiemann, and A.S. Grandy. 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecol. Appl.* 24:560–570. doi:10.1890/13-0616.1
- Mirsky, S.B., M.R. Ryan, J.R. Teasdale, W.S. Curran, C.S. Reberg-Horton, J.T. Spargo et al. 2013. Overcoming weed management challenges in cover crop-based organic rotational no-till soybean production in the eastern United States. *Weed Technol.* 27:193–203. doi:10.1614/WT-D-12-00078.1
- Moore, E.B., M.H. Wiedenhoef, T.C. Kaspar, and C.A. Cambardella. 2014. Rye cover crop effects on soil quality in no-till corn silage-soybean cropping systems. *Soil Sci. Soc. Am. J.* 78:968–976. doi:10.2136/sssaj2013.09.0401
- Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. In: D.L. Sparks, editor, *Methods of soil analysis*. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI. p. 961–1010.
- Olson, K.R., S.A. Ebelhar, and J.M. Lang. 2010. Cover crop effects on crop yields and soil organic carbon content. *Soil Sci.* 175:89–98. doi:10.1097/SS.0b013e3181cf7959
- Pantoja, J.L., K.P. Woli, J.E. Sawyer, and D.W. Barker. 2015. Corn nitrogen fertilization requirement and corn-soybean productivity with a winter rye cover crop. *Soil Sci. Soc. Am. J.* 79:1482–1495. doi:10.2136/sssaj2015.02.0084.
- Parkin, T.B., T.C. Kaspar, and C. Cambardella. 2002. Oat plant effects on net nitrogen mineralization. *Plant Soil* 243:187–195. doi:10.1023/A:1019949727575
- Parkin, T.B., T.C. Kaspar, and J.W. Singer. 2006. Cover crop effects on the fate of N following soil application of swine manure. *Plant Soil* 289:141–152. doi:10.1007/s11104-006-9114-3
- Qi, Z., and M.J. Helmers. 2010. Soil water dynamics under winter rye cover crop in Central Iowa. *Vadose Zone J.* 9:53–60. doi:10.2136/vzj2008.0163
- Qi, Z., M.J. Helmers, R.D. Christianson, and C.H. Pederson. 2011. Nitrate-nitrogen losses through subsurface drainage under various agricultural land covers. *J. Environ. Qual.* 40:1578–1585. doi:10.2134/jeq2011.0151
- Ranells, N.N., and M.G. Wagger. 1997. Nitrogen-15 recovery and release by rye and crimson clover cover crops. *Soil Sci. Soc. Am. J.* 61:943–948. doi:10.2136/sssaj1997.03615995006100030033x
- Ruffo, M.L., and G.A. Bollero. 2003a. Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. *Agron. J.* 95:900–907. doi:10.2134/agronj2003.0900
- Ruffo, M.L., and G.A. Bollero. 2003b. Residue decomposition and prediction of carbon and nitrogen release rates based on biochemical fractions using principal-component regression. *Agron. J.* 95:1034–1040. doi:10.2134/agronj2003.1034
- Sainju, U.M., W.F. Whitehead, and B.P. Singh. 2005. Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. *Agron. J.* 97:1403–1412. doi:10.2134/agronj2004.0274
- SAS Institute. 2009. SAS system for Windows release 9.3.1. SAS Inst., Cary, NC.
- Sawyer, J.E., A.P. Mallarino, R. Killorn, and S.K. Barnhart. 2008. A general guide for crop nutrient and limestone recommendations in Iowa. PM 1688. Iowa State Univ. Coop. Ext. Serv., Ames.
- Sawyer, J.E., and G.W. Randall. 2008. Nitrogen rates. In: G. Laing, editor, *Final report: UMRSHNC (Upper Mississippi Sub-basin Hypoxia Nutrient Committee). Gulf Hypoxia and Local Water Quality Concerns Workshop*, St. Joseph, MI. Am. Soc. Agric. and Biol. Engineers (ASABE), St. Joseph, MI. p. 59–71.
- Schomberg, H.H., J.L. Steiner, and P.W. Unger. 1994. Decomposition and nitrogen dynamics of crop residues: Residue quality and water effects. *Soil Sci. Soc. Am. J.* 58:372–381. doi:10.2136/sssaj1994.03615995005800020019x
- Staver, K.W., and K.B. Brinsfield. 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. *J. Soil Water Conserv.* 53:230–240.
- Steiner, J.L., H.H. Schomberg, C.L. Douglas, Jr., and A.L. Black. 1994. Standing stem persistence in no-tillage small-grain fields. *Agron. J.* 86:76–81.
- Steiner, J.L., H.H. Schomberg, P.W. Unger, and J. Cresap. 1999. Crop residue decomposition in no-tillage small-grain fields. *Soil Sci. Soc. Am. J.* 63:1817–1824. doi:10.2136/sssaj1999.6361817x
- Strock, J.S., P.M. Porter, and M.P. Russelle. 2004. Cover cropping to reduce nitrate loss through subsurface drainage in the northern U.S. Corn Belt. *J. Environ. Qual.* 33:1010–1016. doi:10.2134/jeq2004.1010
- Tabaglio, V., A. Marocco, and M. Schulz. 2013. Allelopathic cover crop of rye for integrated weed control in sustainable agroecosystems. *Italian J. Agron.* 8:35–40.
- Thelen, K.D., and R.H. Leep. 2002. Integrating a double-cropped winter annual forage into a corn-soybean rotation. www.plantmanagementnetwork.org/cm/. Crop Manage. Issue Dec.:0–5. doi:10.1094/CM-2002-1218-01-RS
- Tollenaar, M., M. Mihajlovic, and T.J. Vyn. 1993. Corn growth following cover crops: Influence of cereal cultivar, cereal removal, and nitrogen rate. *Agron. J.* 85:251–255. doi:10.2134/agronj1993.00021962008500020017x
- Tonitto, C., M.B. David, and L.E. Drinkwater. 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. *Agric. Ecosyst. Environ.* 112:58–72. doi:10.1016/j.agee.2005.07.003
- USEPA. 2007. Nitrates and nitrites. Toxicity and exposure assessment for children's health. TEACH chemical summary. USEPA, Washington, DC and ATSDR, Atlanta, GA.
- Vande Hoef, D. 2015. Iowa Department of Agriculture and Land Stewardship press release, Northey: Statewide cost-share available for water quality practices. May 12, 2015. <http://www.iowaagriculture.gov/press/2015press/press05122015.asp> (accessed 22 Sept. 2015).
- Van Roekel, R.R., and J.A. Coulter. 2011. Agronomic responses of corn to planting date and plant density. *Agron. J.* 103:1414–1422. doi:10.2134/agronj2011.0071
- Vaughan, J.D., and G.K. Evanylo. 1998. Corn response to cover crop species, spring desiccation time, and residue management. *Agron. J.* 90:536–544. doi:10.2134/agronj1998.00021962009000040016x
- Vigil, M.F., and D.E. Kissel. 1991. Equations for estimating the amount of nitrogen mineralized from crop residues. *Soil Sci. Soc. Am. J.* 55:757–761. doi:10.2136/sssaj1991.03615995005500030020x
- Williams, A., F.F. Pruski, and M.A. Nearing. 2002. Indirect impacts of climate change that affect agricultural production: Soil erosion. O.C. Doering III et al., editors, *Effects of climate change and variability on agricultural production systems*. Kluwer Academic Publ., Dordrecht, the Netherlands. p. 249–264.